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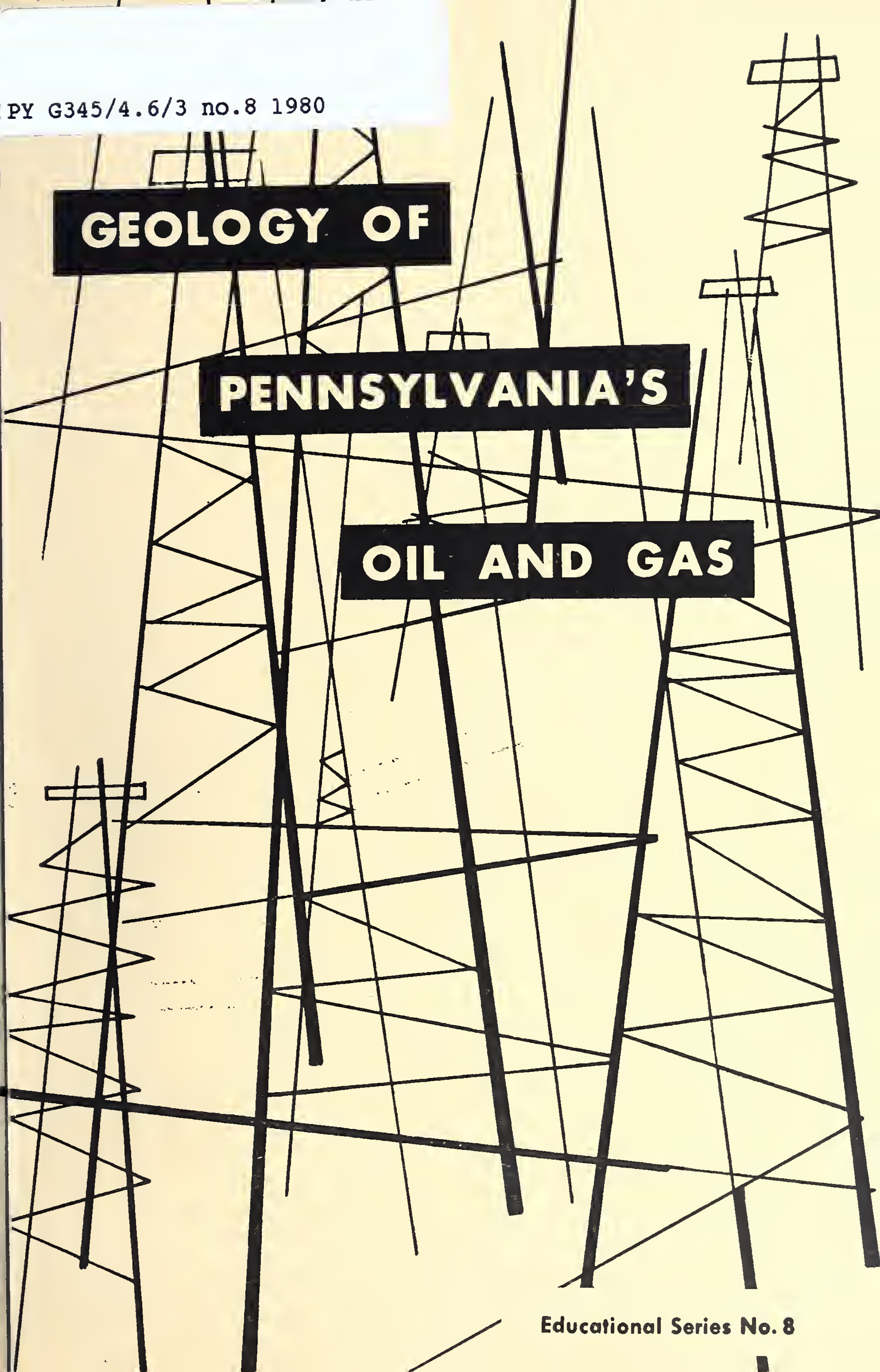
GEOLOGY OF PENNSYLVANIA'S OIL AND GAS



Educational Series No. 8

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF ENVIRONMENTAL RESOURCES
BUREAU OF
TOPOGRAPHIC AND GEOLOGIC SURVEY
Arthur A. Socolow, State Geologist

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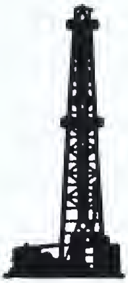
GEOLOGY OF
PENNSYLVANIA'S
OIL AND GAS

by W. R. Wagner
and W. S. Lytle



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GEOLOGY OF
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by

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INTRODUCTION

Petroleum and natural gas have been known almost since the beginning of recorded history. Oil "springs" provided a hardened petroleum called bitumen to the Mesopotamians who lived in the city of Ur in 3000 B. C. The walls of Jericho and Babylon contain mortar made partly from bitumen. Even the word petroleum (*petra*—rock, *oleum*—oil) is ancient; it was originated by the Romans.

Natural gas escaping from the earth was frequently set afire by lightning. These "eternal fires" were worshipped as gods by early civilizations. The ancient Chinese, being more practically minded, piped the gas through tubes of bamboo to heat their homes.

Indians living in western Pennsylvania used the oil springs near Oil City, Pennsylvania, for ceremonial purposes and the colonial settlers became familiar with "Seneca Oil" as a medicine to cure all ailments. The drilling of "Colonel" Edwin Drake's well in 1859 made Pennsylvania the first center of oil production in the world. Oil is not only an important natural resource of this State, but also contributes largely to the economy of the United States and many other countries of the world.

Petroleum and natural gas are used today in countless industries and in most homes. The earliest uses of these resources were in heating, lighting, cooking, and lubrication. Now the main uses are the manufacture of motor fuels such as gasoline and the production of heat. During the past few decades a new industry called petrochemicals has developed in which petroleum is used to make plastics, nylon, teflon, synthetic rubber, medicine, paints and many other new products.

Petroleum and natural gas are extremely important commercial commodities today. Some of the world's largest corporations are concerned with the discovery, refining, marketing, and research of petroleum and natural gas. A considerable part of the energy requirements of the world are fulfilled by the use of these products.

WHAT ARE OIL AND GAS?

Petroleum is the oil obtained from rocks that lie below the surface of the ground. Petroleum is not the only kind of oil. There are animal and vegetable oils such as whale oil and vegetable cooking oil. This booklet deals only with petroleum, and when the word "oil" is used, it is intended as a short word for petroleum.

Oil has a spicy or sweet odor; it varies from a straw-colored, transparent liquid which flows like water to one that is dark and thick like grease. Petroleum produced in Pennsylvania is usually light to dark green and is highly prized because it is used in making lubricating oils.

Natural gas often occurs with petroleum or it may be found by itself. Natural gas is called "natural" to distinguish it from manufactured gas, and being in gaseous form it is quite different from the liquid gasoline bought at service stations for automobiles. Natural gas or simply "gas" is colorless and odorless. Any odor that it has is imparted to it by impurities or small amounts of petroleum. Natural gas, as well as manufactured gas, is used mainly for industrial fuel and for heating of residential homes.

Petroleum and natural gas are composed of the chemical elements carbon (C) and hydrogen (H). Compounds made of these elements form molecules called hydrocarbons. The simplest hydrocarbon molecule contains one carbon atom surrounded by four hydrogen atoms and the chemical formula is written as CH_4 (Figure 1). The CH_4 molecule, called methane, is the predominant molecule that makes up natural gas. More complex hydrocarbon molecules are formed by adding carbon and hydrogen atoms in a chain-like manner to the basic CH_4 molecule. The simpler compounds such as CH_4 (methane) and C_2H_6 (ethane) are gases whereas longer chains such as C_5H_{12} (pentane) are liquid. With increasing additions of carbon and hydrogen atoms to $C_{17}H_{36}$ (heptadecane) the resulting compounds are solid rather than liquid.

Petroleum when taken from the ground is called crude oil and is a mixture of hundreds of different hydrocarbon molecules. The crude oil is transported to refineries where it is refined and separated into many different products. Some of these products are gases, gasoline, kerosene, heating oils, lubricants, waxes, asphalts, and fuel oils.

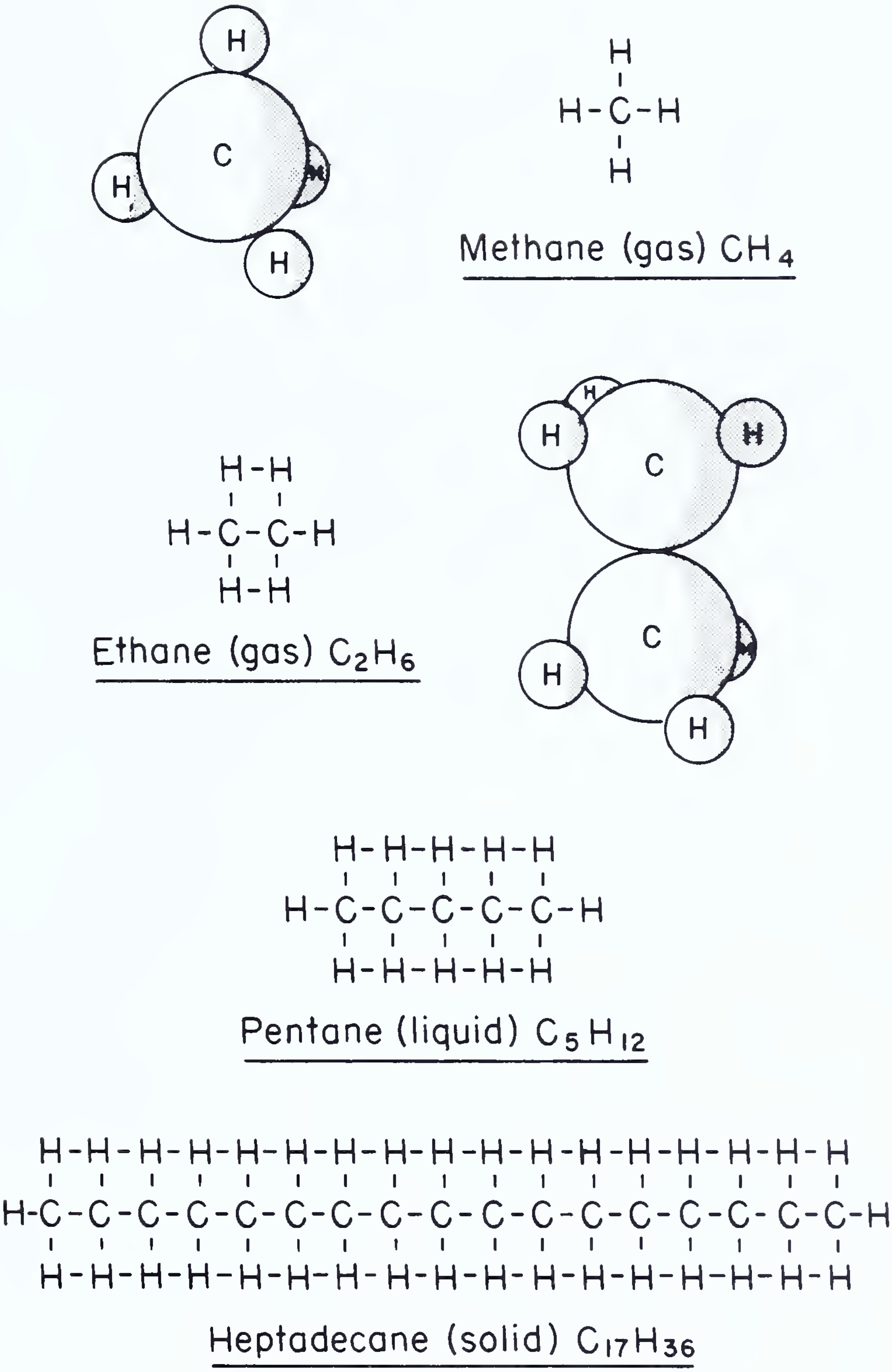

Methane (gas) CH_4
Ethane (gas) C_2H_6
Pentane (liquid) C_5H_{12}
Heptadecane (solid) $C_{17}H_{36}$

Figure 1. Sketches and formulas of hydrocarbon molecules.

HOW ARE OIL AND GAS FORMED?

Most scientists believe that oil and gas originate from the decaying remains of dead plants and tiny animals. The debris of decaying matter collects at the bottom of lakes, swamps, and seas where it is eventually mixed and covered with sediments of mud. Over a period of hundreds of thousands of years sediments accumulate above the organic matter. This overburden of sediment, because of its thickness, exerts heat and pressure which, by processes not well understood, convert the organic matter into droplets of oil and vapors of gas. As a result of the pressure, the mud containing the oil and gas is squeezed into thin layers. The squeezing liberates the oil and gas and they find their way into rocks containing pore spaces or cracks.

The rocks in which oil and gas are formed and from which they are later expelled are called source rocks. Rocks with pore spaces or cracks are called reservoir rocks; they are usually sandstones and limestones. Source rocks are commonly dark-colored shales containing much organic matter. After the oil and gas are freed from the source rock, the process by which they travel into the reservoir rocks is called migration. Reservoir rocks and migration will be discussed later in this report.

WHERE ARE OIL AND GAS FOUND?

GENERAL REMARKS

Petroleum and natural gas are found in underground, sedimentary rocks that contain openings or voids. The important three words are "underground", "voids", and "sedimentary". Only underground, in the subsurface rocks, can large quantities of petroleum accumulate and be preserved. Occasionally petroleum from underground seeps to the surface and accumulates as a tarry scum in pools or springs. Rarely is this oily deposit of a sufficient amount to be of commercial value because natural destructive processes at the earth's surface work to destroy it. Natural gas is lost much more easily than oil because it is a gas and immediately disappears into the atmosphere.

Voids are any openings such as cracks and holes in the rocks, or open spaces between individual grains of the rock where the grains are not a perfect fit. In subsurface rocks these voids are filled with fluid which can be water, natural gas, or oil. Because rocks are not uniform masses, they vary in composition. Even with rocks of the same composition, voids are present in varying amounts.

Sedimentary rocks are the usual home of petroleum and natural gas because the organic material that is converted to hydrocarbons is incorporated into the sediment during deposition, and also because voids are common. Igneous and metamorphic rocks are formed under conditions very unfavorable to the occurrence and preservation of organic material and consequently are less likely to contain petroleum and natural gas. Also, voids are less abundant in igneous and metamorphic rocks. Igneous rocks, formed from molten material, possess an interlocking network of crystals and tend not to develop voids between the crystals. In metamorphic rocks, voids that may have been present are usually destroyed by the intense heat or pressure that forms these rocks.

Sedimentary rocks commonly consist of particles. The particles, whether they are fragments of shells cemented together into limestone, or microscopic bits of clay which accumulate into shale, or grains of sand which make up sandstone, do not fit perfectly against each other but leave tiny voids between each particle. Other sedimentary rocks such as limestones and some dolomites are formed by precipitation of chemical particles from sea water. These rocks often contain only minor voids between the particles, but larger voids commonly develop because portions of the rock are easily dissolved.

Sedimentary rocks containing numerous voids are present in western Pennsylvania. This concentration partly explains the location of the oil and gas fields of the State as shown in the map in the middle of the booklet. The oil fields in pink and the gas fields in shades of green are restricted to western and northern Pennsylvania. In southeastern Pennsylvania, around the Philadelphia area, most of the rocks are metamorphic and igneous, lack voids, and have little chance of bearing hydrocarbons. The distribution of the oil and gas fields also depends on other factors which will be discussed in another part of this publication.

STRATIGRAPHY

Many kinds of scientists study sedimentary rocks. One of these is the geologic specialist known as a stratigrapher, who divides and classifies the thousands of feet of sedimentary rocks into units called formations. A formation is a unit of rock deposited under uniform or similar conditions; it may be a few feet thick or a thousand feet thick. The formation is the foundation upon which larger rock sequences are recognized. Sequences of formations, one on top of another, are combined to represent large divisions of time called periods. Periods, in like manner, are grouped to give even larger time intervals called eras. Geologic time throughout the world has a number of major eras which from oldest to youngest are: 1) the Precambrian Eras; 2) the Paleozoic Era; 3) the Mesozoic Era; and 4) the Cenozoic Era in which we live.

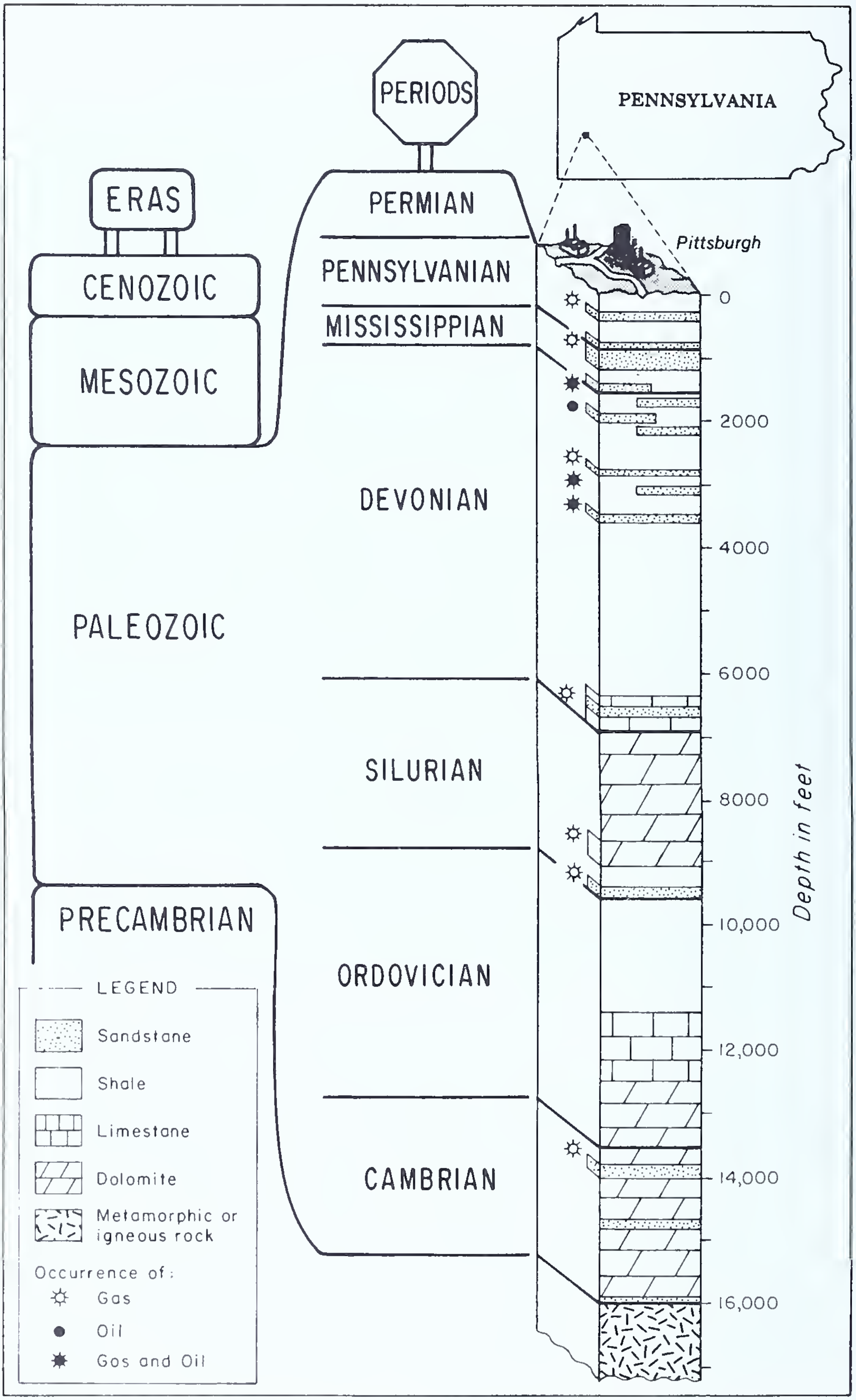


Figure 2. Stratigraphic column of subsurface rocks at Pittsburgh, Pennsylvania.

Rocks from all of the eras are present in Pennsylvania, but those of the Paleozoic Era are particularly well represented. Paleozoic age rocks cover the surface of the whole State except for parts of southeastern Pennsylvania. The rocks of this era are subdivided to represent seven periods from Cambrian, the oldest, to Permian, the youngest (Figure 2). In fact, one of the periods of the Paleozic Era, the Pennsylvanian Period, is named for rocks now exposed at the surface of western Pennsylvania.

Figure 2 shows the sequence of formations in the subsurface rocks near Pittsburgh. Below the surface at Pittsburgh are 16,000 feet of sandstone, shale, limestone, and dolomite, all of which were deposited during the Paleozoic Era. The Paleozoic Era includes the following periods from oldest to youngest: Cambrian, Ordovician, Silurian, Devonian, Mississippian, Pennsylvanian, and Permian. Underneath this sedimentary rock sequence is an even thicker interval of igneous and metamorphic rocks formed during the Precambrian Eras.

The circles with radiating spokes (Figure 2) indicate that oil and gas in western Pennsylvania are found in the rocks of all the Paleozoic Periods except the Ordovician and the Permian. Only in recent years have the rocks of the Cambrian Period entered the ranks of the gas producers. The gas production is from one field in the northwestern corner of the State. One of the reasons for limited production from the Cambrian rocks and none from the Ordovician is that few test wells have been drilled to these rocks because they are very deep and costly to drill. Less than 50 wells of the 300,000 drilled in Pennsylvania have reached the Ordovician and Cambrian rocks. Most of the production from Silurian rocks lies in the northwestern Pennsylvania counties of Erie, Crawford, and Mercer. The main productive formations of the State are of Devonian age and are present throughout the western half of Pennsylvania. Pennsylvanian and Mississippian production is located mainly in southwestern Pennsylvania. No production is obtained from the Permian rocks because they are just below the surface in the southwestern counties of Washington and Greene. Rocks just below the earth's surface rarely have petroleum or natural gas because they are flushed out and replaced by fresh surface waters.

PETROLOGY

A petrologist is another geologic specialist who studies rocks. He analyzes the properties of individual particles of the sedimentary rock such as size, shape, and chemistry. In oil and gas studies he is particularly interested in those geologic processes that create and fill in the voids. Voids in rocks are measured in terms of two aspects, porosity and permeability. Porosity is the amount of open space in the rock compared to the total volume of rock; this is commonly reported in terms of percent. Thus, in a rock with 20 percent porosity, one-fifth of the overall rock volume is actually made up of open spaces. Permeability measures the ease with which fluids move through connected voids. A very porous rock may contain many voids full of fluid, but if the voids are not connected to one another, the rock is impermeable because the fluids cannot be transmitted. For rocks to yield commercial amounts of oil or gas they must be both highly porous and permeable, and they must also contain oil or gas.

The large oil and gas deposits of the world come from sandstones, limestones, and dolomites. Porosity in sandstones occurs as voids between the grains, and as fractures. In limestones and dolomites porosity commonly is due to solution of the rock or chemical alteration. Most of the world's production so far has come from sandstones, but limestones and dolomites contain nearly half of the remaining petroleum reserves still in the ground, indicating that limestones and dolomites are becoming increasingly important as productive sources. The production trend in Pennsylvania tends to parallel the world trend. Production has come primarily from sandstone formations, as can be seen in the sequence of formations under Pittsburgh (Figure 2). Future exploration in Pennsylvania should look for reserves in the deeper limestones and dolomites of Cambrian, Ordovician, and Silurian age.

OIL AND GAS FIELDS

The essential features of an oil and gas deposit are:

1. That the sandstone, limestone, or dolomite is porous and permeable. Because of their capacity to contain and transmit fluids, such rocks are called reservoir rocks.
2. That the fluids in the reservoir rock are oil and gas rather than water.
3. That the reservoir rock is enclosed by impermeable layers that prevent the escape of the oil and gas. Shale, an extremely fine-grained, impermeable rock, commonly acts as a seal that traps the oil and gas in the reservoir rock.

Those areas where commercial quantities of oil and gas are known to be trapped are called oil and gas fields. A field may be divided into smaller pools. In the center fold of this publication is the Oil and Gas Fields Map of Pennsylvania. The green areas represent many gas fields where natural gas has been or is now being produced, and the pink patches show oil fields where petroleum has been found. The light-green gas fields indicate shallow production from rocks of Pennsylvanian, Mississippian and the upper part of the Devonian Periods. The dark-green gas fields represent production from the deeper, older rocks of the Devonian Period and the Silurian and Cambrian Periods.

The most extensive oil and gas field belt of Pennsylvania is shown by the broad band of pink and light-green pools and fields stretching from the southwest corner of the State northeastward into Warren and McKean Counties of northern Pennsylvania. In this band the United States' first oil well was drilled in 1859 and today, over 100 years later, the area still produces much of Pennsylvania's gas and almost all of its oil. Most of the oil and gas of this belt occurs in sandstone reservoirs of Late Devonian age. The reservoirs are generally long in a northeast direction and short in a northwest direction. Many have been interpreted as representing ancient sand bars and beaches deposited at the edge of a shallow sea which covered parts of western Pennsylvania in Late Devonian time (Figure 3). Some of the sand bars and beaches were many miles long and only a few miles wide. The bars stuck above the surface of the sea several miles offshore and separated the open sea from the lagoon which lay between the bars and the shore. While sand accumulated on the bars and beaches, mud and clay were deposited in the lagoon and in the open sea. Today the bar and beach sands are porous and permeable sandstones, the clay and mud of the former lagoon and open sea are shales, and all of these environments of deposition are buried hundreds of feet below younger deposits of shale and sandstone. Thus, the important conditions for an oil and gas trap are satisfied. The

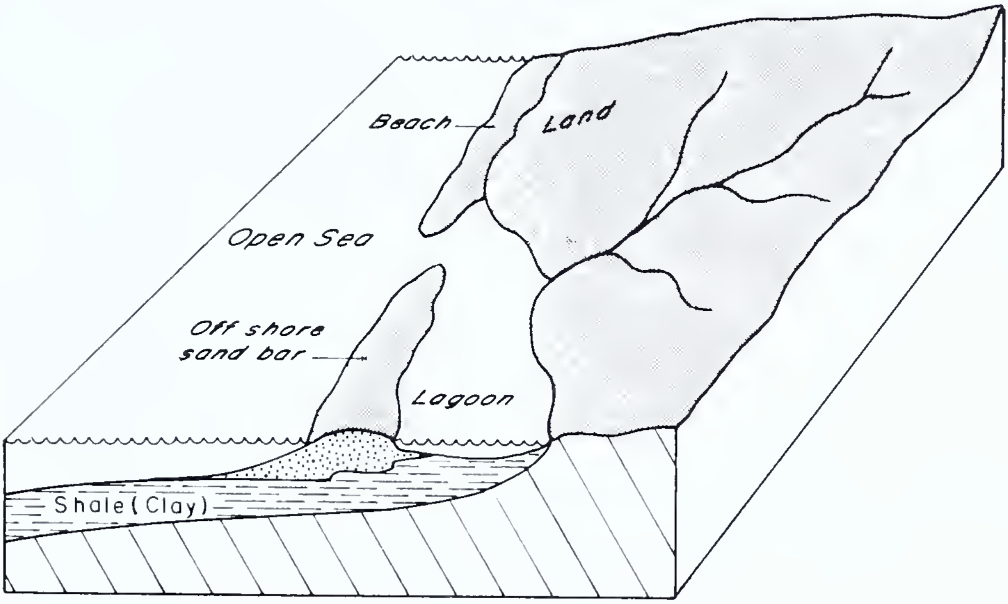


Figure 3. Environments of deposition of beach sands and offshore bars which became the shallow oil and gas fields of western Pennsylvania.

sandstone becomes the reservoir in which oil and gas accumulate and the overlying and the laterally adjacent shales seal the oil and gas in the reservoir.

The example of the nearshore deposits of the Upper Devonian rocks illustrates the trapping of oil and gas in rocks where only a few changes have taken place since deposition. The main change is the hardening of the sediments into rock. Trapping is also caused by changes in the rock type or a change in the continuity of the rock. These kinds of traps are called *stratigraphic traps.*

A second class of oil and gas trap is the *structural trap* in which the rocks have been broken or warped from their original position. This trap is the result of changes in the form of the reservoir rock. The scientist who studies movements of sedimentary rocks after they have been deposited is called a structural geologist.

STRUCTURAL GEOLOGY

Almost all sediments, whether chemically derived or composed of fragments, are layered somewhat like a cake and were deposited in a horizontal or nearly horizontal position. Each layer is called a bed. During a span of hundreds of thousands of years, many beds, one above another, accumulated on the sea floor and built up a thickness which may total several miles. The weight of the overlying beds exerted pressure on the underlying layers causing compaction and cementation of the lower layers into rock. If a vertical slice of an area, where much sediment has accumulated, is removed from the earth and viewed from the side, a series of gently warped layers can be seen (Figure 4). Such an area is called a depositional basin, being thickest in the center where most of the sediment accumulated and becoming thinner toward the margins.

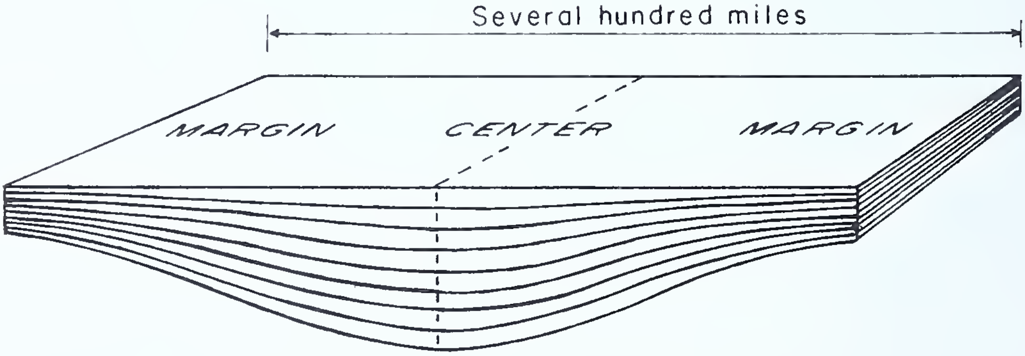


Figure 4. Shape of depositional basin.

Sediments after being hardened into rocks do not always remain in their originally, nearly flat position. Commonly, as a result of forces within the earth, the layers may be tilted or even bent into arches called anticlines and troughs called synclines. The layers are no longer horizontal. Figure 5 shows what happens to a layer of rock when it is folded. Stage 1 of the figure represents a flat layer and the arrows indicate the

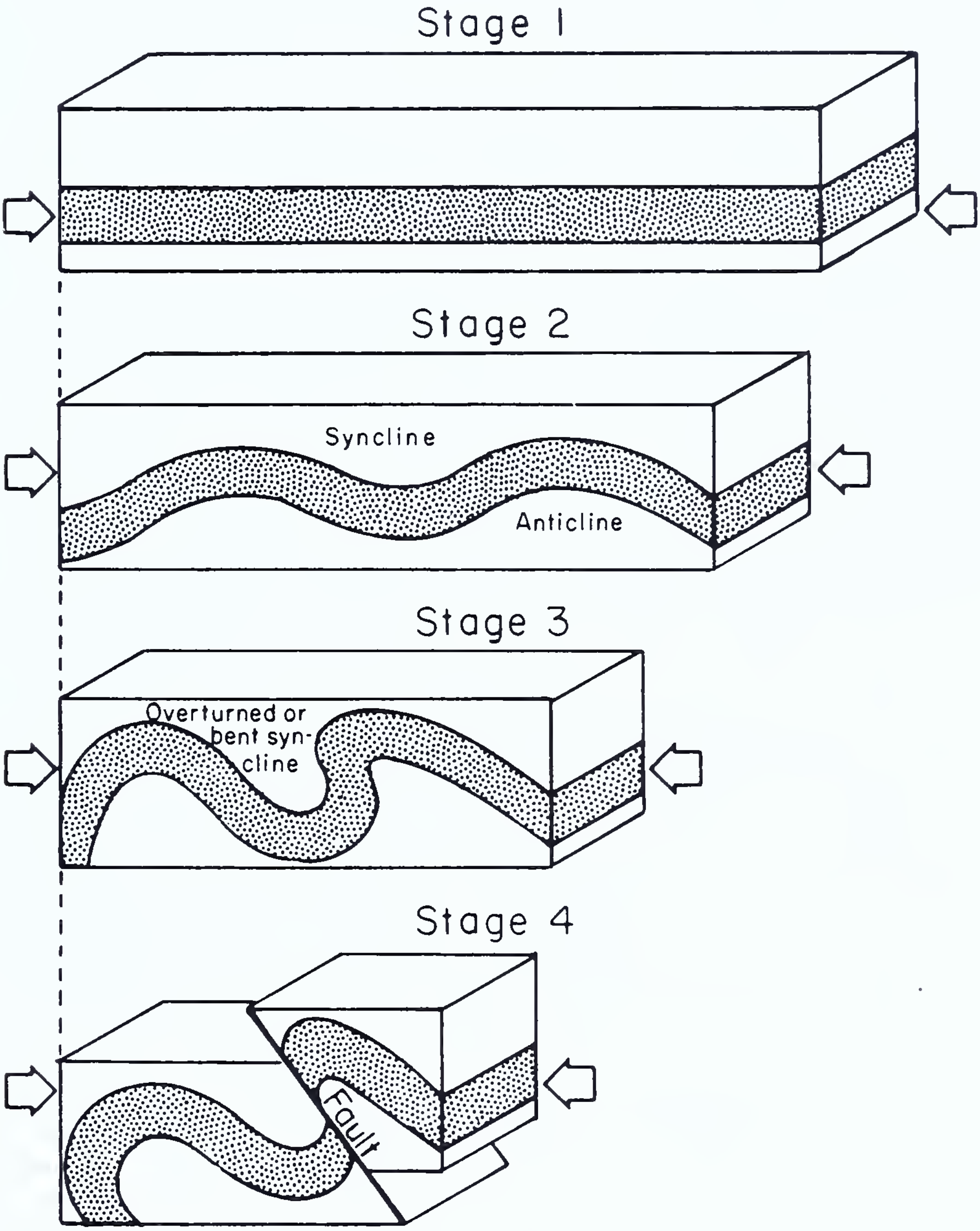


Figure 5. Folding and faulting of a layer of rock.

direction of force or pressure applied to the layer. In stage 2 the pressure has folded the layer into a gentle anticline (up-fold) and syncline (down-fold). If the force continues, as in stage 3, the folds themselves become bent or overturned. In stage 4 the pressure becomes so great that the layer breaks and moves out of the place where it is being squeezed. The plane along which the layer breaks and moves is called a fault.

Figure 6 is a sketch of a vertical slice through the sedimentary basin of western and central Pennsylvania. At the left or western end is Pittsburgh and at the right or eastern end is Harrisburg. Several hundred million years ago this basin once looked like the one in Figure 4, but during the formation of the Appalachian Mountains, near the end of the Paleozoic Era, the basin was folded and faulted. Most of these structural changes occur in the central Pennsylvania half of the basin from Altoona eastward. Here the rocks of Ordovician age, shown by the gray pattern, contain both upright and overturned anticlines and synclines. Four large faults, represented by the heavy black lines, cut the rocks into repetitive sections. Approximately two miles below Altoona the Ordovician rocks are broken by one of the faults. If a very deep well were to be drilled at Altoona, it would pass through the Silurian, Ordovician and Cambrian rocks several times. West of Altoona, in the western part of the State, the folding and faulting are much diminished and the rocks are only slightly changed from their original horizontal position. The Ordovician rocks appear almost flat and the much younger Mississippian rocks, shown by the dotted pattern, have broad, gentle folds compared to the folds in the rocks farther to the east.

STRUCTURAL TRAPS

Folding and faulting of a formation causes changes in the shape of the reservoir rocks and these changes can result in the development of structural oil or gas traps.

Folding of a reservoir rock layer affects the contained gas, oil, or water. Before folding occurs, these fluids may be dispersed throughout the rock layer, but after the anticlines and synclines develop, the gas being the lightest fluid will rise in the layer to the crest of the anticline. Oil will lie just below the gas, and water, the heaviest fluid, will collect in the reservoir layer on the flanks of the anticline and in the syncline (Figure 7).

Another kind of structural trap is caused by faulting. Figure 8 shows a tilted and faulted group of shale-sandstone-shale beds. The movement along the fault causes the sandstone reservoir to butt against a shale bed. The shale bed plus those shales above and below the sandstone reservoir act as a seal resulting in oil and gas being trapped in the upper end of the reservoir layer.

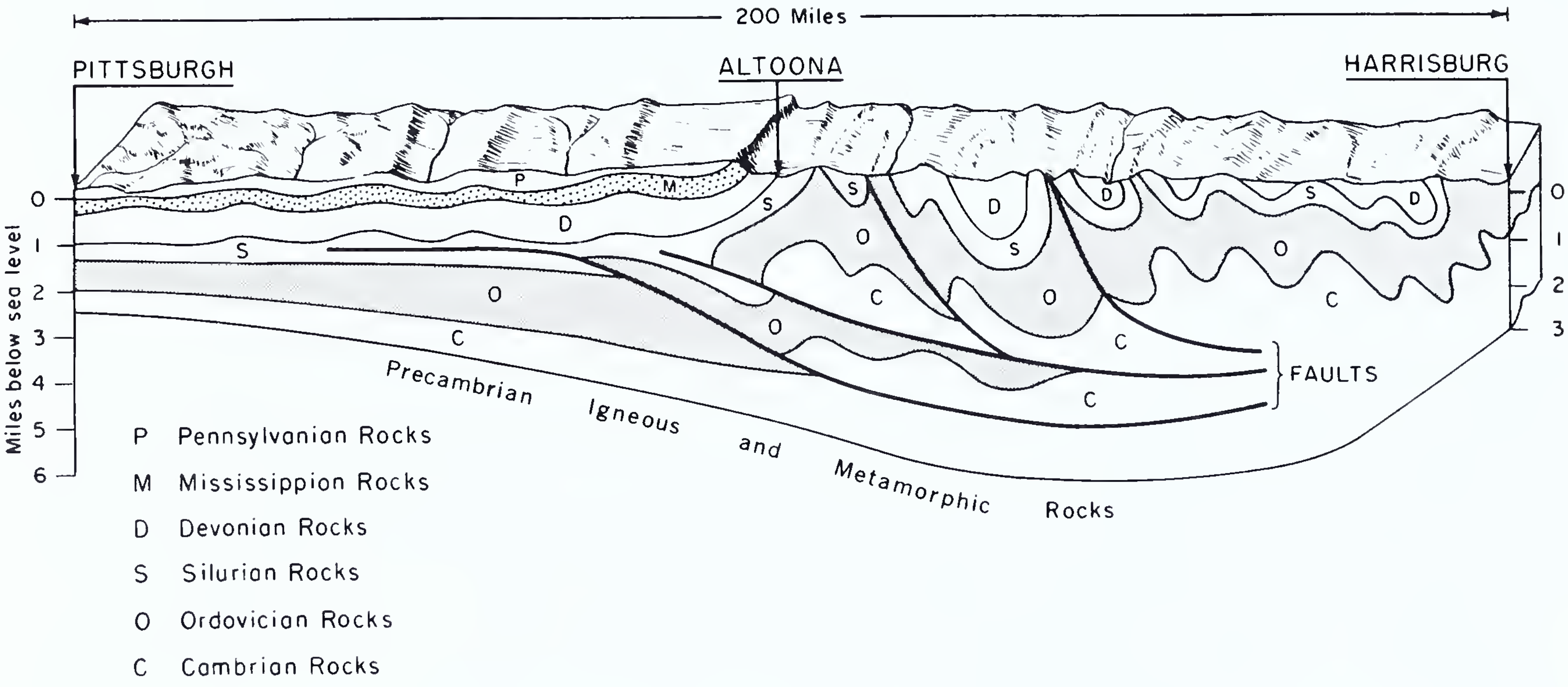


Figure 6. Cross section from Pittsburgh to Harrisburg showing folding and faulting of subsurface rocks.

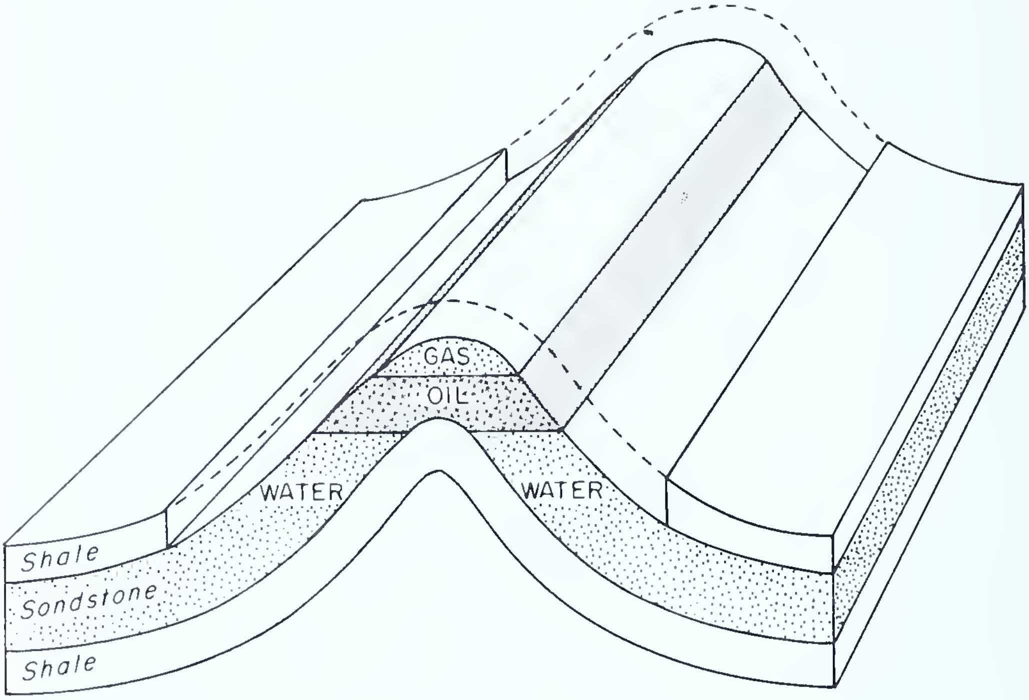


Figure 7. Entrapment of oil and gas in an anticline.

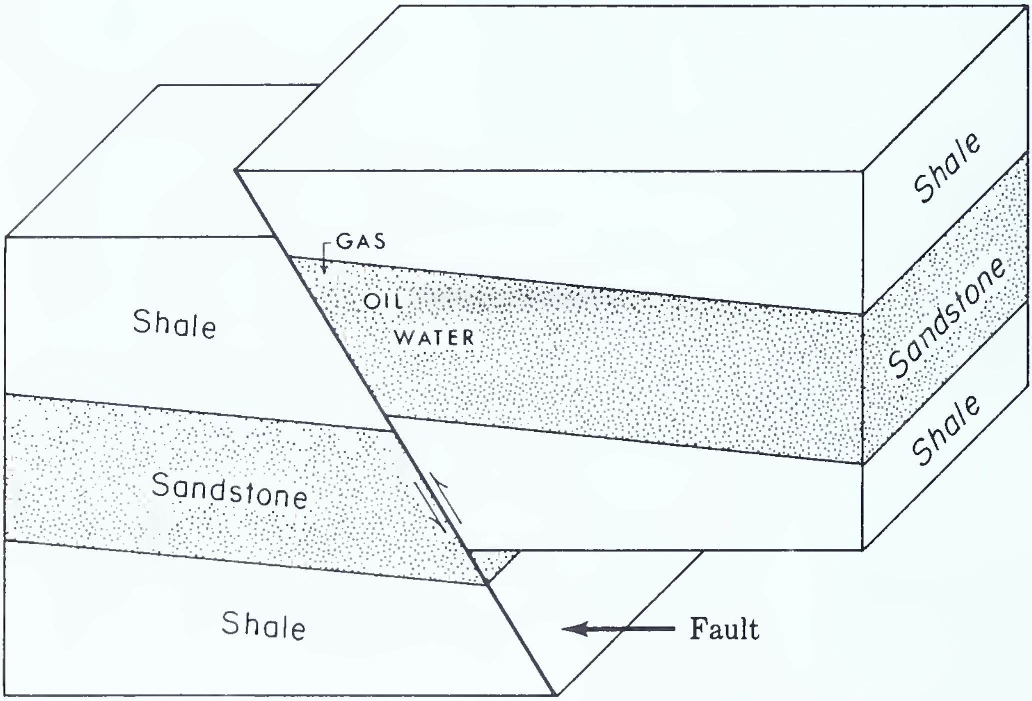
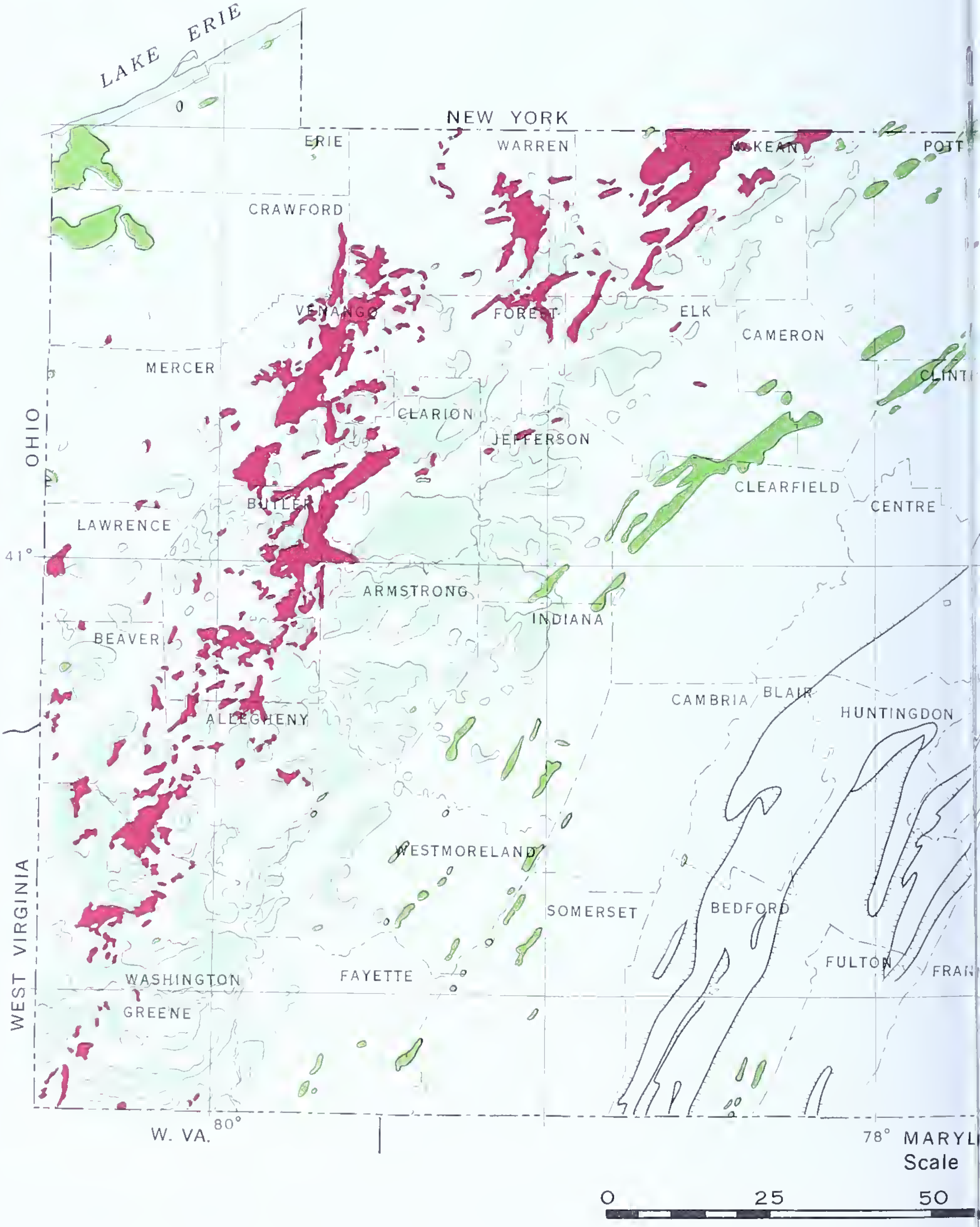


Figure 8. Entrapment of oil and gas by faulting.

MAP 10

OIL AND GAS FIELDS MAP



PENNSYLVANIA

COMMONWEALTH OF PENNSYLVANIA
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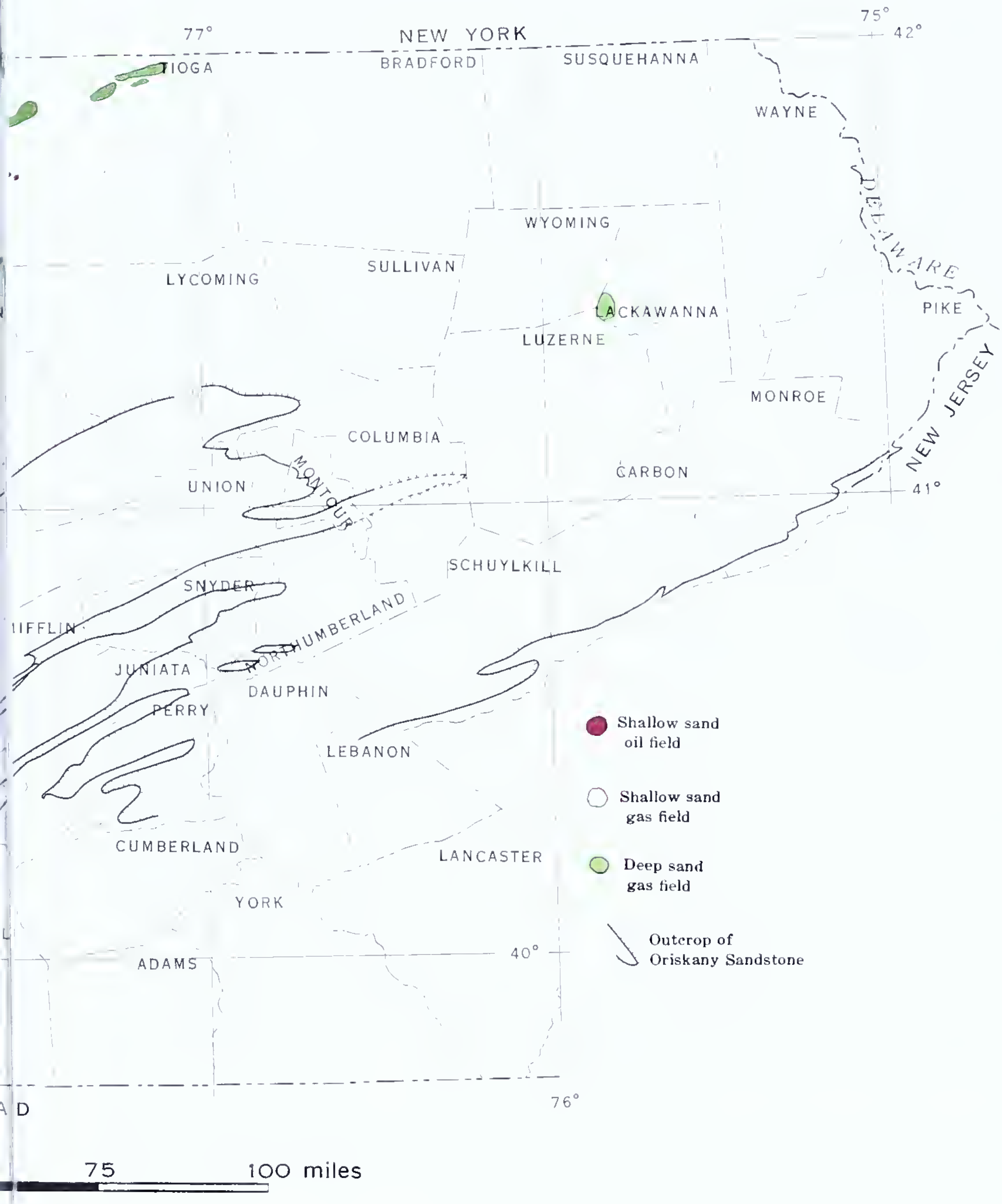
Arthur A. Socolow, State Geologist



Most of the structural traps in Pennsylvania occur along a northeast trending belt extending from Fayette County on the southwest to Potter and Tioga Counties on the northeast. This belt is shown on the Oil and Gas Fields Map (Center fold map) by a scattering of fields colored dark green. These fields have produced gas from a rock formation of Early Devonian age called the Oriskany sandstone. The dark-green fields in this structural belt, and also in the northwest corner of the State, are called deep sand gas fields because they lie several thousand feet below the fields colored pink and light green. The Oriskany sandstone is 4,500 to 5,000 feet deep in Potter and Tioga Counties and becomes deeper to the southwest; in Fayette County it is 8,000 to 8,500 feet deep.

Figure 9 is a section through the anticline containing the Leidy gas field, Clinton County. The location of the section is shown by line A-B in the inset map. Near the surface, as can be seen by the arching of the sandstone bed, the anticline is a smooth, gentle fold, but 4,000 to 6,000 feet below sea level the structure is more complex. Here the Oriskany sandstone and an overlying formation, the Tully limestone, are both folded and faulted. In the Oriskany sandstone are two gas pools separated by faults, the Leidy pool and the Tamarack pool. Because of the

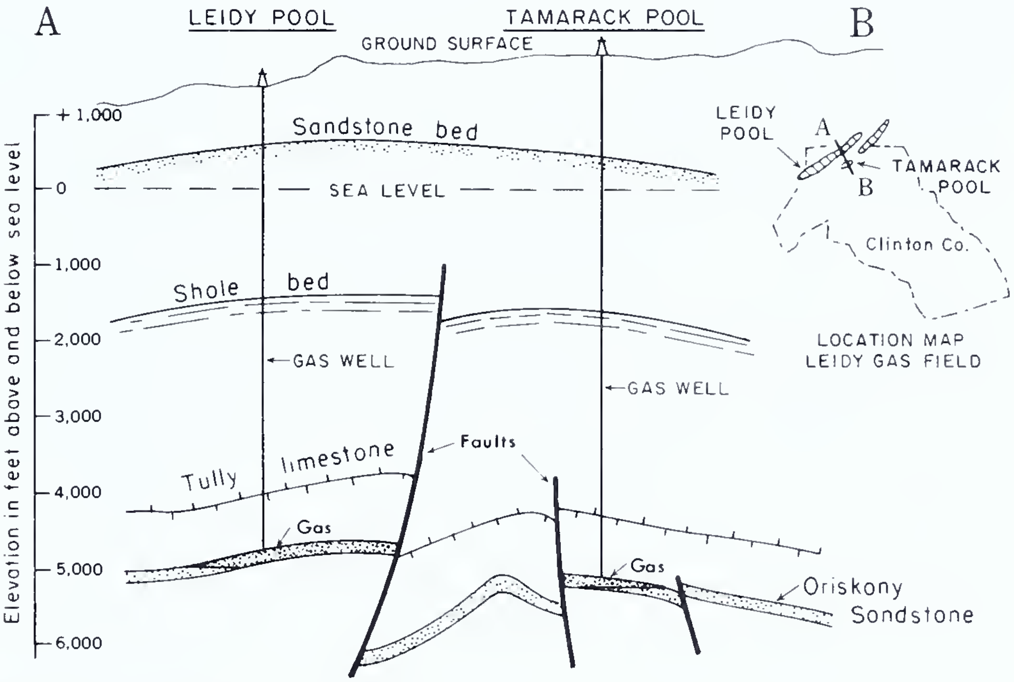


Figure 9. Cross section of Leidy gas field. Entrapment of gas in folded and faulted anticline. Note that faults in Oriskany and Tully disappear before reaching surface.

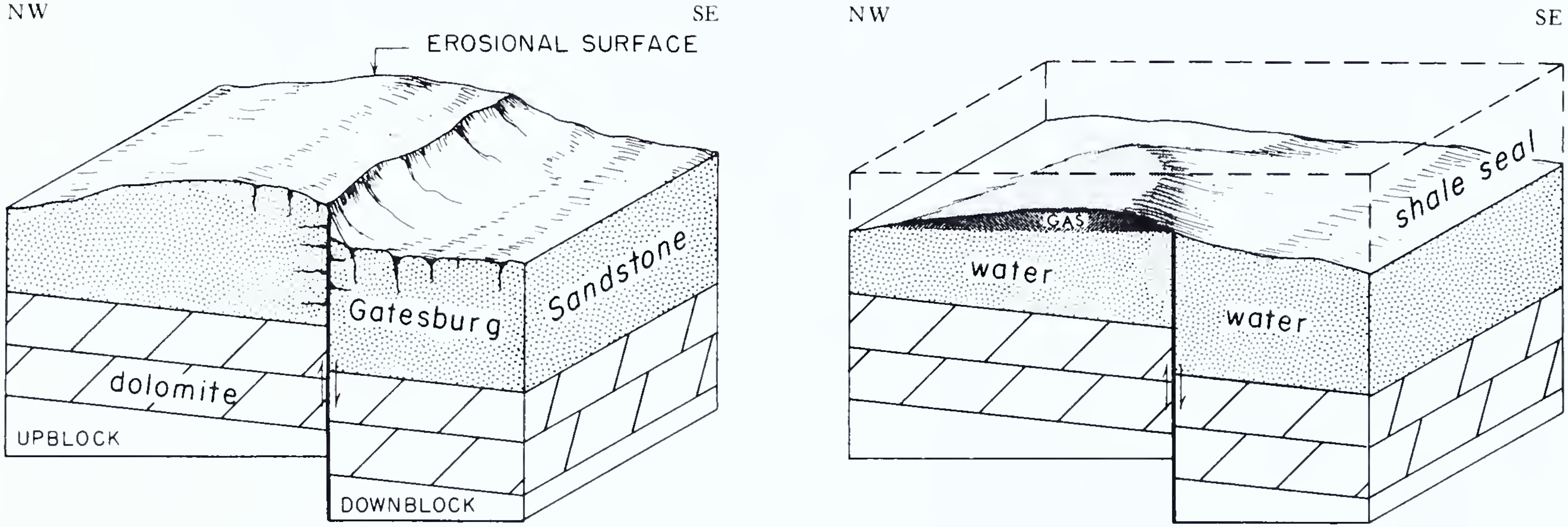
faulting, the main gas trap, the Leidy pool, lies on the northwest side of the anticline near the crest rather than on it. The Tamarack pool, a trap containing less gas, is in one of the faulted sections at the crest. The Oriskany sandstone in the field is about 35 to 40 feet thick. No oil was found in this field so consequently the water in the reservoir layer lies directly below the gas.

The structure of the Leidy gas field is typical of the belt from Potter to Fayette Counties where gentle anticlines at the surface are faulted in subsurface permitting entrapment of gas primarily on the flanks instead of the crest of the anticline. This structural belt is intermediate in complexity between very little folding and faulting near Pittsburgh and a great amount of folding and faulting from Altoona eastward. In the slice (or cross section) of Figure 6 the anticlines of the Potter-Fayette County belt appear as wide, gentle ripples that become less complex westward toward Pittsburgh. From Altoona eastward the folds and faults increase in size many times.

Most of the world's oil and gas fields have been found on anticlines. Therefore, central Pennsylvania with its large anticlines should be an ideal hunting ground for oil and gas, but until now the only productive fields in this area are in Bedford County which produces gas from the Oriskany sandstone in folded and faulted anticlines. The reason for the lack of productive fields in central Pennsylvania is not well understood. One possible explanation is that so few wells have been drilled that the presence or absence of oil and gas has not been properly evaluated. A more pessimistic answer is that oil and gas may have been present at one time but was either destroyed or pushed out of central Pennsylvania because of *too much* structural deformation.

COMBINATION TRAPS

A third type of oil and gas trap is the combination trap in which both structural and stratigraphic features are combined. A combination gas trap occurs in the Gatesburg sandstone of Cambrian age in northwestern Pennsylvania. The discovery well is located at a depth of 6,300 feet in the center of a large gas field in western Crawford County (large green area on the Oil and Gas Fields Map). Figure 10 is a northwest to southeast section through the gas field and it illustrates the history of the trap. Part (a) shows that the dolomite and Gatesburg sandstone which were deposited horizontally have been tilted up to the northwest. Faulting accompanied the tilting and caused the southeastern part of the section to drop down. The tilting raised the Gatesburg out of the sea, where it was originally deposited, and exposed it to erosion. Erosion carved hills and valleys into the Gatesburg surface, forming an erosional



a. Farmation af erosianal surface and creation af permeability by raising Gatesburg sandstane above level af sea

b. Depasition of averlying shale acts as roof to prevent escape af gas that collects belaw the erasional surface

Figure 10. Combination gas trap in Gatesburg sandstone, Crawford County.

surface. Water entered the fault and created an increase in the porosity and permeability of the sandstone by dissolving some of the dolomite that cements the sand grains together. Part (b) of Figure 10 shows that millions of years later the sea returned to northwestern Pennsylvania and deposited a formation of shale over the Gatesburg erosional surface. Then more millions of years after the deposition of the shale, gas and water migrated up the tilted Gatesburg sandstone and the gas was trapped where the sandstone ended at the erosional surface. The overlying shale acted as a seal to prevent the gas from entering formations which lie above the sandstone.

The discovery well drilled on the high side of the fault found a cap of gas above the water, whereas a well that was drilled on the low side of the fault encountered only water. The field is a combination trap because the development of the erosional surface, which planes off the Gatesburg sandstone, is of stratigraphic origin and the fault, which raises the northwest block above the water zone, is a structural contribution. Both conditions were necessary to form the trap.

HOW TO FIND OIL AND GAS

The finding of oil and gas today requires the cooperative efforts of many trained persons: geologists, physicists, and engineers. Each person has a part in one of the three phases of operations: the exploration phase, the drilling phase, and the completion phase.

EXPLORATION PHASE

Oil companies, in seeking new oil and gas fields, look for sparsely drilled sedimentary basins that may contain sandstone, limestone, or dolomite reservoirs in subsurface. Such an area is exemplified by central and northeastern Pennsylvania where the potential reservoirs exist and few test wells have been drilled. When a prospective basin is located, many thousands of acres of land are leased from property owners by the oil company. The company pays the owner for the right to drill wells on property which the oil company does not own.

Once the land is leased, the field geologist examines the rocks exposed at the surface in hillsides, roadcuts, and stream valleys. He measures the tilt of beds and plots on a map the trends of anticlines, synclines, and faults. He divides the rocks into formations, and charts the direction in which they become thicker or thinner, and where they change from one rock type into another. From wells that have already been drilled he relates the subsurface formations to those at the surface and tries to locate zones of porosity by small amounts of water, oil, or gas which may have been reported on the well record. By these methods of geologic surface and subsurface mapping, geologists try to narrow a prospective area to an ancient shoreline trend, a pinch out of a reservoir formation, or a structural trap such as an anticline.

Greater detail on subsurface structure is supplied by a geophysicist who is a physicist applying the laws of physics to the rocks of the earth. This scientist conducts a seismic survey over the prospective area. By setting off small explosions in the ground, shock waves like tiny earthquakes travel through various rocks at different speeds. Some of the shock waves are reflected like an echo from the formations and return to the ground surface where they are recorded by a detector station (Figure 11). Formations such as limestone and sandstone are stronger reflectors of shock waves than are shales. The time taken for waves to travel down and be reflected back tells how deep the formation is. From a network of shot points and detector stations the structure of the formations can be interpreted.

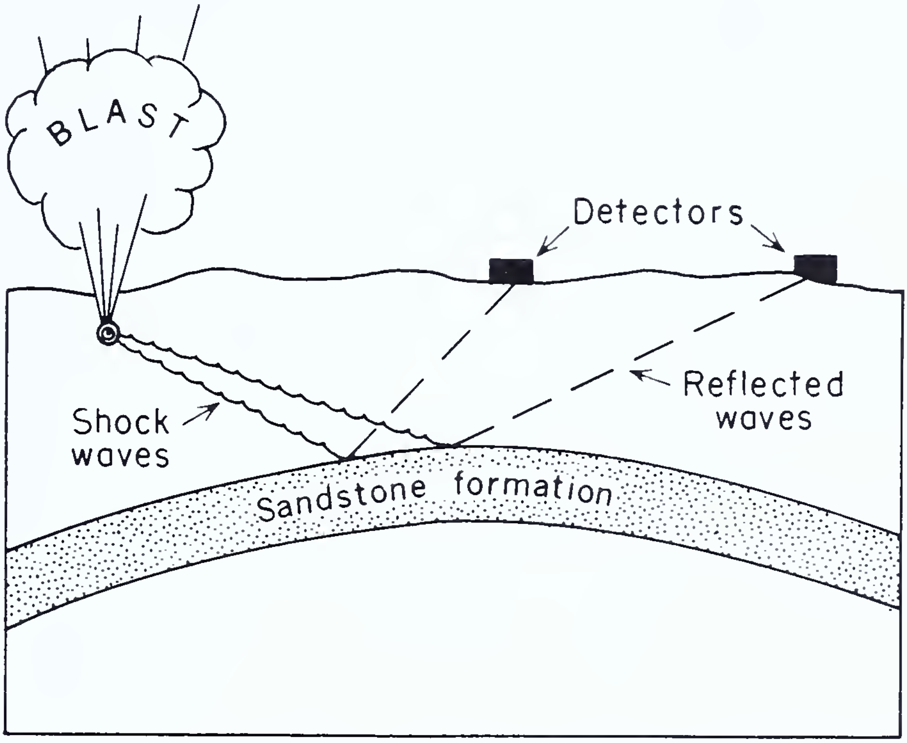


Figure 11. Reflection of shock waves from sandstone formation indicates subsurface structure.

DRILLING PHASE

When the preliminary work of the geologist and geophysicist is complete, and if the results have been encouraging, a drilling location is prepared. The only sure way to determine if oil or gas is present is to drill. A well located several miles from a producing field is called a wildcat well. Assuming that the exploratory interpretations were correct, the well will find a porous and permeable reservoir and if oil or gas are present it will become a producer. If only water is found the well will be abandoned as a "dry hole." In spite of the scientific contributions to the exploration of oil and gas only one wildcat well out of every nine drilled is a discovery well, a well that discovers a new supply of oil or gas.

The two methods used in drilling wells in Pennsylvania are the cable tool method and the rotary method (Figure 12). In cable tool drilling a steel .frame called a derrick is erected; it may be up to 80 feet high. From the derrick is suspended a wire cable that holds the drilling tools. At the end of the tools is the drilling bit, a heavy steel chisel that is hoisted by the cable and let fall under its own weight. This process, driven by an engine, is repeated in rapid succession resulting in a hole created by pulverizing the rock. At intervals, the bit is taken from the hole and the rock fragments are removed. Geologists examine these rock fragments to identify the formations through which the well passes. As the hole deepens, it may be lined with steel casing to prevent the walls from caving.

The cable tool method with modern refinements is now being used in Pennsylvania to drill many wells up to 4,000 feet deep. Occasionally a much deeper well is drilled by this method.

The rotary method, like the cable tool, also uses a derrick, but one that may reach 200 feet high. The deeper the well, the larger the derrick that is needed. The drilling bit is made of steel teeth attached to a hollow tube called the drill pipe. At its upper end, the drill pipe is clamped to a rotary table which, powered by an engine, causes the drill pipe and the bit to turn. The rotating bit cuts through the rock in a manner similar to the action of an electric drill through a piece of wood. As the hole becomes deeper, sections of drill pipe are added at the top. To cool the bit and to flush the drill cuttings from the hole, a fluid is pumped down the inside of the drill pipe, out through holes in the bit, and up the space between the drill pipe and the wall of the hole. As the fluid rises in the hole it carries the rock fragments with it. In many areas the fluid pumped down the hole is a specially prepared heavy mud, but in most wells in Pennsylvania compressed air is used rather than mud. Most of the wells drilled below 4,000 feet in the State use the air rotary method because it drills much faster than the cable tool method.

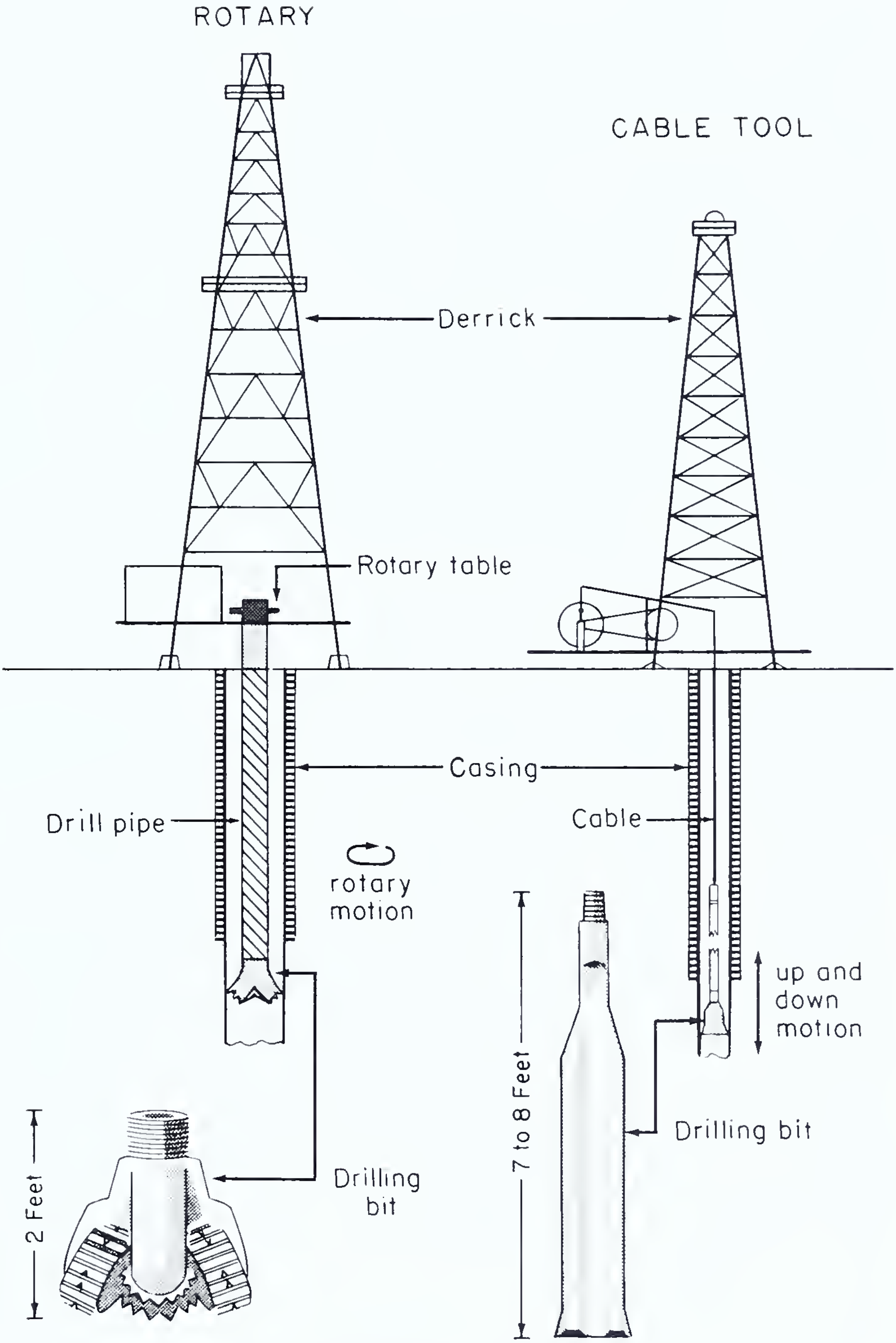


Figure 12. Rotary and cable tool methods of drilling.

After being drilled, many wells do not produce oil or gas. In some cases the hydrocarbons are absent simply because none exist in the anticipated formation. The well is then a dry hole. In other cases, however, abundant oil or gas may be present but cannot reach the well because the permeability of the formation is low. The completion phase of finding oil or gas increases the permeability of a formation by artificial means, thereby turning a potential dry hole into a producing well.

To determine what completion method to use, a geologist or a petroleum engineer will examine the drill cuttings and have the well "logged". "Logging" a well means to lower into the hole an instrument that measures the electrical properties, amount of the radioactivity, and the density of the formations penetrated. After analysis of the logged data and relating of this information to the character of the rock, a completion program can be prepared for a formation. The two main completion methods are acidizing and fracturing (Figure 13).

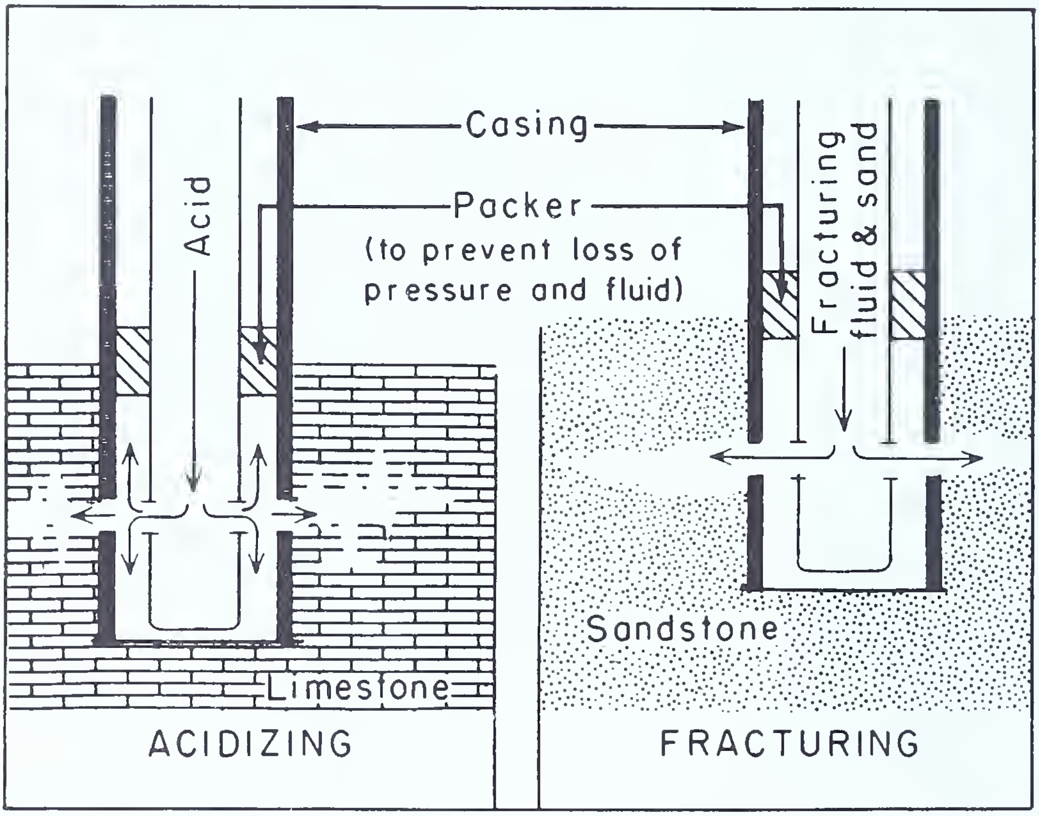


Figure 13. Increasing permeability by acidizing and fracturing.

In acidizing, acid is pumped into the rocks in order to dissolve some of the carbonate near the well bore, thus creating greater permeability. The rocks most easily dissolved by acid are limestones and dolomites which are composed of carbonates. Sandstones also react to the acid treatment where the grains of sand are cemented by carbonate minerals.

The other method used to increase permeability is fracturing. In this method rounded sand grains in a liquid such as water or kerosene are injected into the formation. The sand and liquid are pumped in under such tremendous pressure that the formation is actually cracked open. When the pressure is released and the cracks begin to close, the injected sand acts as a prop keeping the fractures open. The fractures are the paths by which oil or gas enter the well.

Because of the low permeability of most of the State's reservoirs, almost all the wells drilled during the past few years have been completed with the fracturing method. Fracturing in Pennsylvania is so successful that old producing gas wells drilled decades ago are being re-entered and fractured, resulting in considerable increase in gas flow.

HISTORY OF OIL AND GAS IN PENNSYLVANIA

Figure 14 is a map of western Pennsylvania showing the location of the oil and gas fields mentioned in the following historical summary.

OIL HISTORY

Along Oil Creek, just south of Titusville, Pennsylvania, on August 27, 1859, two men, one a former railroad conductor named Edwin Drake and the other a salt well driller called "Uncle Billy" Smith, struck oil at a depth of 69½ feet. "Colonel" Drake's well marks the birth of the world's oil industry. Other wells preceded Drake's, but his was the first to create a commercial interest in oil production. By the end of 1861, the commercial demand caused over 2½ million barrels of oil to be removed from the ground. Drilling was so active that most of the oil fields of Venango County were discovered by 1870.

In 1871 the Bradford oil field in McKean County was found. The Bradford field is the largest in the State; its development began in 1875 and the peak yearly production of almost 23 million barrels was reached in 1881.

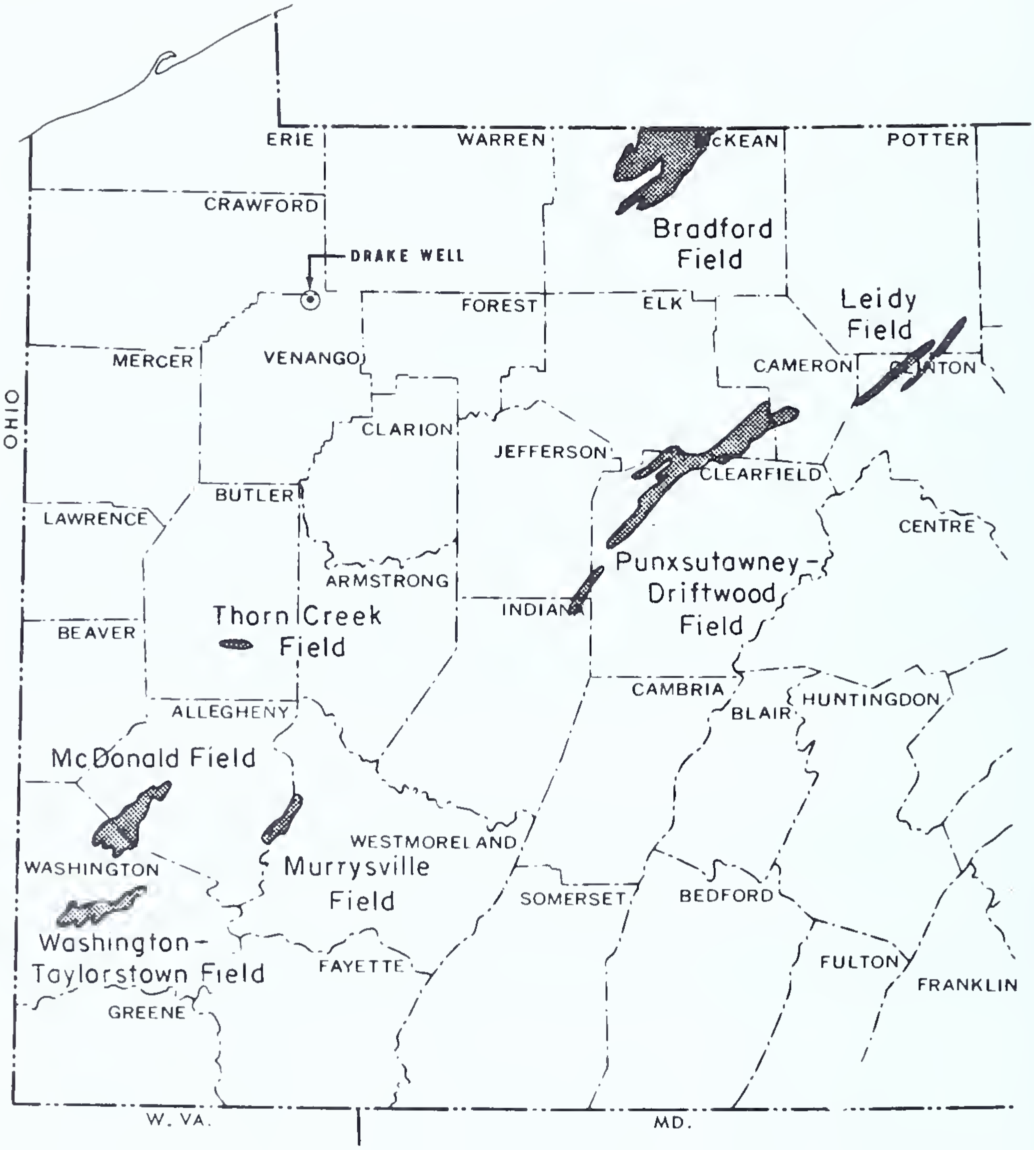


Figure 14. Location of oil and gas fields mentioned in historical summary.

As the Bradford field production declined, new areas of discovery were established in southwestern Pennsylvania. In the Thorn Creek field south of Butler in Butler County, the Armstrong Number 2 well brought to the surface an estimated 10,000 barrels of oil during its first 24 hours of life. The Washington-Taylorstown field in Washington County and the McDonald field in Allegheny and Washington Counties added millions of barrels to Pennsylvania's rapidly rising oil production. Two of the largest oil wells in the State were located in the McDonald field. They are the Mathews Number 1 and the Mevey Number 1; both produced between 500 and 850 barrels of oil per hour.

Pennsylvania was the center of the world oil industry during the late 1800's and was the leading oil producer until 1895.

Figure 15 shows two graphs. The solid line graph represents the State's oil production by years and the dashed line graph shows the oil production from the Bradford field. The main characteristic of both curves is the double peak or hump representing periods of high production. Between the humps is a valley of low production. The first hump in the State's oil curve occurs from the late 1870's to the late 1890's and represents the discovery and development of the new Bradford, Thorn Creek, Washington County, and McDonald fields. After this development, or primary recovery, came the slump of the early 1900's to the middle 1920's. The period of slump or decline would have continued up to the present had it not been for the discovery that more oil can be obtained from oil fields by a method called secondary recovery.

Primary recovery does not remove all the oil trapped in a reservoir. From 60 to 90 percent may remain underground because of lack of pressure to force the oil into the well. Under natural conditions, oil is pushed

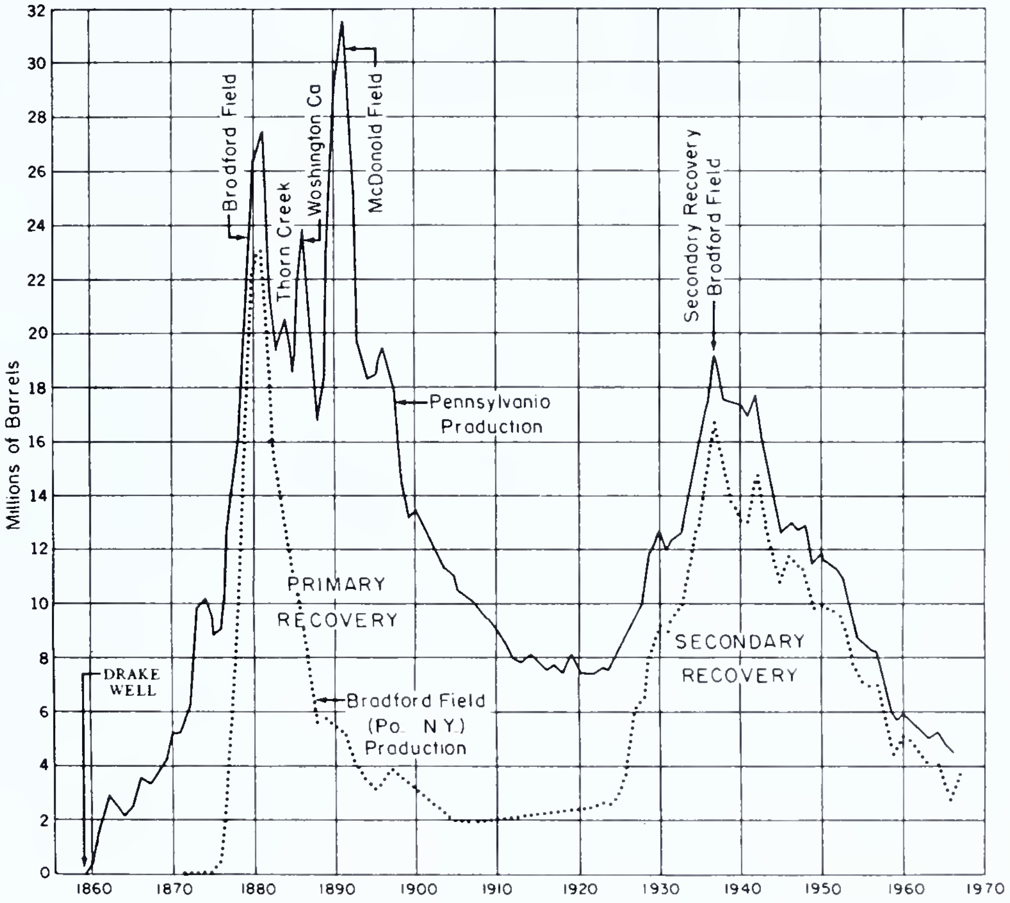


Figure 15. Annual production in Pennsylvania. Solid line—total State production. Dashed line—Bradford field production (also includes production from New York portion of field).

into a well by the pressure of gas or water. When this pressure is greatly lowered the small amount of oil entering the well may be uneconomical to produce. With secondary recovery methods the pressure is raised and maintained by artificially injecting water, gas, or air into certain wells called input wells. The injected fluids carry or push the oil in the reservoir from each point of injection to the producing wells.

During the thirty years from the middle 1920's to the middle 1950's the second peak of oil production was due to secondary recovery methods, particularly in the Bradford field. The curve of the Bradford field closely parallels the State curve indicating that most of Pennsylvania's oil comes from secondary recovery operations in the Bradford field.

Since the middle 1950's, the oil production has been dropping. The reasons for the decline are that almost all the oil to be obtained from secondary recovery in the Bradford field has now been produced, and little exploration to find new oil fields is being undertaken. To reverse this decline and begin a third peak in the production curve, undrilled areas of the State must be carefully examined for their oil potential, secondary recovery methods must be attempted in fields where they have not yet been tried, and new experimental methods of oil recovery called tertiary recovery must be successful.

NATURAL GAS HISTORY

The commercial development of natural gas came after the oil boom of the 1860's to early 1880's. During these years gas was used as fuel to drive the engines at oil wells and to heat individual buildings. The rapid expansion of the gas industry began in 1884 when gas was piped from the Murrysville gas field into Pittsburgh. One of the main factors in the development of the steel industry in Pittsburgh was the piping of gas, because for many years it sold at such a low price that the cost of manufacturing was greatly reduced.

Until 1930 all the gas production came from the shallow sand reservoirs of Mississippian and Late Devonian age (light-green fields on the center fold map). In 1930, wells drilled below 4,000 feet discovered gas in the Lower Devonian Oriskany sandstone in Tioga County. Gas was also found in the rocks of Early Silurian age in Erie County in 1947 and in the Cambrian rocks of Crawford County in 1964. All of these deeper reservoirs are shown in dark green on the center fold map.

The graph of yearly production of gas in Pennsylvania (Figure 16) shows an irregular but gradual decline from 138 billion cubic feet of gas in 1906 to 75 billion in 1949. Interrupting the decline is a peak from

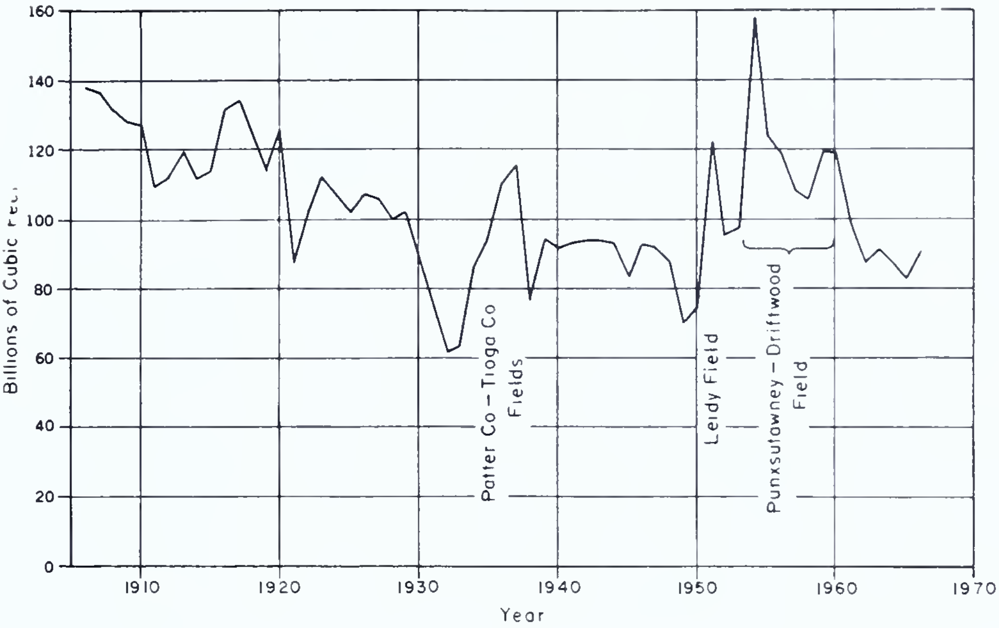


Figure 16. Annual production of natural gas in Pennsylvania.

1934 to 1937, which represents the first Oriskany production from fields in Potter and Tioga Counties. The spurt of production from 1951 to 1960 and the record high of 158 billion cubic feet of gas in 1954 is due to the discovery of more Oriskany gas from faulted anticlinal traps in Clinton, Cameron, Elk, and Clearfield Counties. The two giant gas fields are the Leidy field and the Punxsutawney-Driftwood field (Figure 14). In the Leidy field is the largest producing gas well east of the Mississippi River; it is the Finnefrock Number 1, which, on discovery in 1951, produced over 150 million cubic feet per day from the Oriskany sandstone. An average Oriskany gas well yields about 5 million cubic feet per day.

Pennsylvania uses almost five times more gas than it produces. This demand for gas has resulted in the conversion of drained gas traps into storage reservoirs. Gas is piped into Pennsylvania from western states and is stored in these drained reservoirs in the summer and used in the winter when the demand is greater. In 1960 there were 61 gas storage fields in the State.

The demand for gas will continue to rise. To maintain or increase gas production new fields will have to be discovered in northern or western Pennsylvania. The occurrence of gas in Bedford County is a positive indication that much more gas may be present in the complex folds and faults of central Pennsylvania.

ADDITIONAL READING ON OIL AND GAS

THIS FASCINATING OIL BUSINESS, by Max W. Ball, Douglas Ball and Daniel Turner. Bobbs-Merrill, 2nd edition 1965. A complete discussion of the oil industry from exploration to drilling to transportation and refining.

Booklets published by the American Petroleum Institute, 1271 Avenue of the Americas, New York, New York 10020.

1. SCIENCE IN THE SEARCH FOR OIL
2. SCIENCE IN THE PETROLEUM INDUSTRY
3. CHEMISTRY AND PETROLEUM
4. CAREERS IN THE OIL INDUSTRY

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